Saimaa University of Applied Sciences
Technology Imatra
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DETERMINATION OF STRENGTH PROPERTIES OF PINE AND ITS COMPARISON WITH BIRCH AND EUCALYPTUS

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ABSTRACT

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The purpose of this bachelor's thesis was to analyze the strength properties of pine (*Pinus Sylvestris*) Kraft pulp required for paper making process. This thesis also compares the result with the earlier study done on birch *(Betula pendula)* and eucalyptus *(Eucalyptus Grandis)* which were part of an ongoing research on different wood species and their properties by Saimaa University of Applied Sciences, Imatra.

In the experimental part, two different types of Kraft pulp were studied; one with low lignin content and the other with high lignin content. These pulps were obtained after pulping fresh pine chips in liquid circulated batch digester by Kraft pulping process. Screened pulps were beaten in PFI mill to different degrees. Handsheets were made with Rapid Köthen equipment. Different strength and optical properties were measured from the prepared sheets. This study on pine is compared with the earlier studies done on birch and eucalyptus. The result reflects basic comparison of pine with birch and eucalyptus but does not deal with details.

Although these species could not be compared directly due to various pros and cons of individual species, general conclusions were derived. Long and strong fibres of pine pulped by Kraft process provides possibility to manufacture strong and durable end product, whereas birch and eucalyptus are well known for good formation, superior opacity and in addition to that, they could be bleached to higher brightness level compared to pine. If these species are combined, the end product will be much better compared to one particular species.

Keywords: Comparison, Scots Pine, Silver Birch, Eucalyptus, Strength, Kraft, Sulfate pulp, Beating, Chemical pulping.

CONTENTS

1 INTRODUCTION

The purpose of this thesis is to determine the strength properties of pulp and paper made from Scots pine (*Pinus Sylvestris*), pulped by Kraft process. In addition, the purpose is to find the behaviour of different properties of pulp, which changes with increasing beating degree. Later the comparison would be done with the initial studies done on birch *(Betula pendula)* and eucalyptus *(Eucalyptus Grandis)*.

In the theory part, softwood is introduced. Pine from the aspect of physical and chemical properties is explained and later focus is shifted to Scots pine. Then, general comparison is made among pine, birch and eucalyptus to point out the differences among these species in terms of growth properties, process properties, physical characteristics etc. Chemical pulping is described, whereas more emphasis is given on Kraft pulping, as our entire experiment is based on Kraft pulping method. Theory part is concluded with brief explanation of beating and its effect on fibre properties.

The experiments required for this study were carried out in the facilities of Saimaa University of Applied Sciences in Imatra. The standards followed for this study are listed in appendix 4.

2 SOFTWOOD

2.1 General

Forests of the world contain a great number of species, which may be divided into two groups: coniferous trees, usually called softwood, and deciduous trees, or hardwood. Conifers are cone-bearing seed plants with vascular tissue; all extant conifers are woody plants, the great majority being trees with just a few being shrubs. Typical examples of conifers include cedars, douglas-firs, cypresses, firs, junipers, kauris, larches, pines, redwoods, spruces, and yews. With seven extant families, 68 genera, and 545 species, classification of the extant conifers remains controversial. (Britannica 2010)

The term softwood is used as opposed to hardwood, which is the wood from angiosperm trees. Softwoods are not necessarily softer than hardwoods. In both groups there is an enormous variation in actual wood hardness, with the range in density in hardwoods completely including that of softwoods. Some hardwoods (e.g. balsa) are softer than most softwood. This is not surprising as there are about a hundred times as many hardwoods as there are softwoods. The woods of longleaf pine, douglas-fir, and yew are much harder in the mechanical sense than several hardwoods.

Softwood is comprised of two types of cells: tracheids (90-95%) and ray cells (5-10%). Softwood fibres are by definition wood tracheids. Tracheids give the softwood mechanical strength (particularly thick-walled latewood tracheids) and transports water. Softwood fibres are closed at both ends. The median fibre length of Finnish pine and spruce is approximately 3 mm. Due to their long fibres, softwood pulps are often referred to as long fibre pulps. (Gullichsen & Fogelholm 2000)

Here in Finland, softwoods used for paper production are pine *(Pinus Sylvestris)* and spruce *(Picea abies)*. The same types of softwood species are generally used in Europe and Asia as in Finland, with deciduous species also being used to a certain extent, e.g. larch (Larix). Due to its high extractives content, larch is not as suitable a raw material for pulp as spruce and pine. North American softwood species differ from European and Asian species. In the northern regions of North America Douglas-fir, hemlock, ponderosa pine, white and black pine, and balsam fir are used as pulpwood. In the southern United States various pine species (southern pine) are used. In fast-growing plantation forests in, for example, South America and New Zealand, radiata pine is commonly used. (Knowpulp)

The various softwood species do not greatly differ from one another in terms of chemical composition. The greatest difference is the extractives content and composition. Extractives limit the usability of certain species in sulfite processes and the production of mechanical pulp, but not in sulphate processes. Pulp made from pine species is usually produced using a sulphate method, while spruce is used as a raw material in the production of mechanical pulps.

Table 2.1 Chemical composition of various softwood species (% of dry wood weight). (Sjöström 1993, p.23*)*

Species	**Common name**	**Extractives**	**Lignin**	**Cellulose**
Pinus radiata	Monterey pine	1.8	27.2	37.4
Pinus sylvestris	Scots pine	3.5	27.7	40
Picea abies	Norway spruce	1.7	27.4	41.7
Larix sibirica	Siberian larch	1.8	26.8	41.4

In Table 2.1 above, it can be seen that the proportion of extractives, lignin and cellulose differ within softwood itself. Scots pine contains highest amount of extractives and lignin among above mentioned species.

2.2 Pine

According to Pravdin (1969), pines are coniferous trees in the genus "*Pinus*", in the family "*Pinaceae*". They make up the monotypic subfamily "*Pinoideae*". Many botanists consider the genus *Pinus* having been divided into two subgenera: *Strobus* and *Pinus* (also known as Haploxylon and Diploxylon especially in forestry literature). *Haploxylon*, or soft pines have one fibrovascular bundle; *Dip-*

loxylon, hard pines have two. The genus *Pinus* as now understood consist of 25-30 species in the subgenus *Haploxylon* and 70-80 species in the subgenus *Diploxylon*, growing in Eurasia and North America. According to the number of vascular bundles *P.sylvestris* belongs to subgenus *Diploxylon* Kohene.

The pines occupy a prominent place in the plant kingdom. Though with a little over one hundred there are not nearly as many species as in some other genera of plants, pines constitute a group which has proved to be remarkably successful in adaptation to very different environments. As a result of this success, we can find species of pine in almost every terrestrial habitat, growing naturally in the northern hemisphere or being introduced (and often naturalised) in the southern hemisphere. In some region pines are the dominant trees in extensive forests and in many other parts they co-dominate, usually with conifers and sometimes with angiosperm. (Farjon 2005)

Pines are woody plants and usually trees, sometimes shrubs (with more than a single steam), which contain resin in their parts and have “evergreen” foliage leaves in the shape of linear needles. Pines are gymnosperms, meaning plants with ‘naked seeds’, as opposed to angiosperms, which have seeds enclosed in carpels, forming a fruit. Among gymnosperms, the conifers, to which pine belongs, are natural groups, i.e. they are derived from a single common ancestor. In pines both male and female reproductive organs are found on the same tree (trees are monoecious). (Farjon 2005)

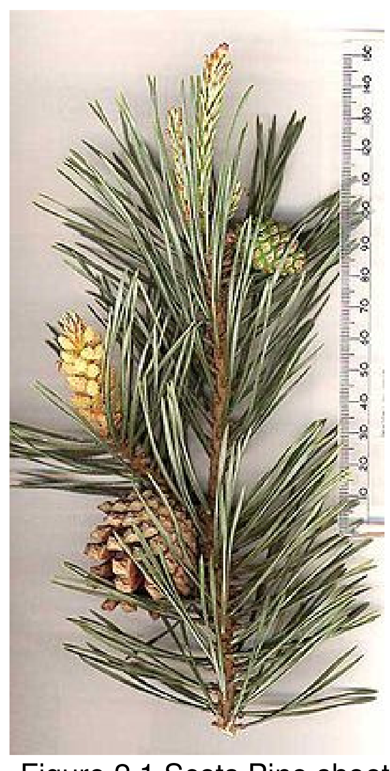

Figure 2.1 Scots Pine shoots (Wikipedia)

In figure 2.1, it could be seen that, Scots Pine shoot in spring with two-year old seed cone (open, brown), one-year old seed cone (green), and new seed cones (red) and pollen cones (yellow).

The Scots Pine is an evergreen tree, when grown under optimal conditions, attains a height of 35 m, but most trees are not higher than about 25 m. The bark is thick and scaly on the lower trunk, breaking in irregular plates, purplish brown turning grey, higher up towards the crown and on the branch it is papery thin, flakes and orange-brown. The young shoots are green at first, later turning light brown, glabrous, usually rough with cataphyll bases. (Farjon 2005)

The ability of the Scots pine to thrive under different ecological conditions - from the extreme north to the subtropics, in the long polar day and the short day of south, with the short growing season in the north and long one in the south, under absolute winter minimum air temperature of – 60 °C and an absolute maximum of 40°C or more, at low humidity, low edaphic moisture and nutrients, in swamps and sands - is the cause of its wide distribution on the Eurasian mainland from 70° to 37° N. and from 7° W. to 138° E. (Pravdin 1969)

Scots Pine (*Pinus Sylvestris*) is an important tree in forestry. It is a popular tree for planting on open and poor industrial sites because it can survive on poor soils. A seedling stand can be created by planting, sowing or natural regeneration. Commercial plantation rotations vary between 50-120 years, with longer rotations in north-eastern areas where growth is slower. (Forestry Commission GB and Scotland).

In Finland and the Scandinavian countries, generally softwoods used for paper production are Scots pine. It was used for making tar in the pre-industrial age. There are still some active tar producers, but mostly the industry has ceased to exist. It has also been used as a source of resin and turpentine.

2.3 Structure of pine

In general, structure of pine could be described by figure 2.2.

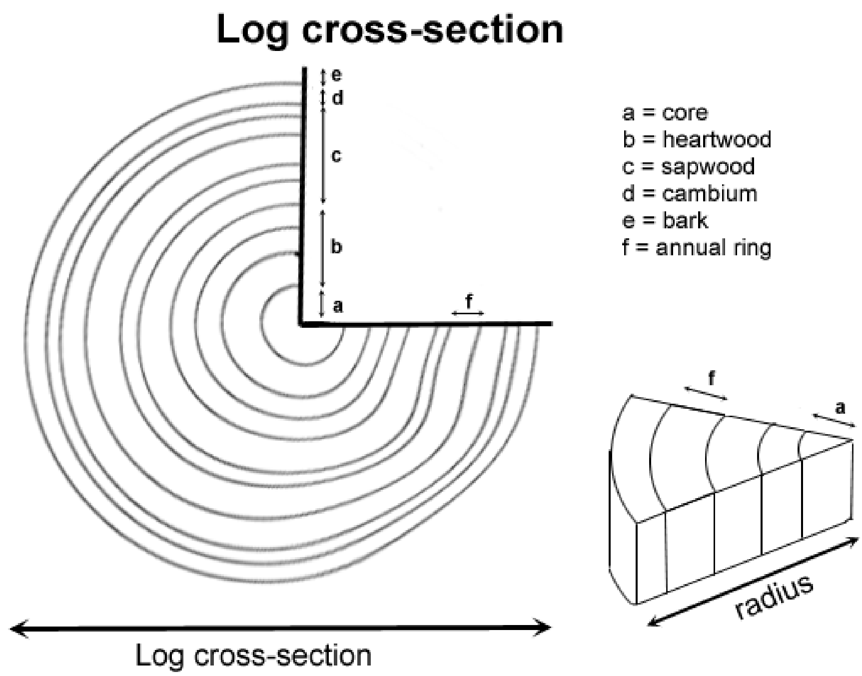

Figure 2.2 Schematic diagram of log cross section. (Knowpulp)

The above figure 2.2 describes the softwood structure in which core, heartwood, sapwood, cambium, bark and annual ring could be seen as layer by layer from inside out. The cambium is a tissue of living cells surrounding the sapwood. It is a thin layer of cells where cell growth takes place. The rate of growth varies with the season and the growth place, giving rise to the deposition of thin-walled fibre cells in the spring and dense thick-walled fibres in the summer. It is dormant during the cooler months of the year. This yearly growth cycle is responsible for the annual rings phenomena. The cambium is surrounded by bark, whose two layers can be distinguished by their colour: the living inner bark (phloem) and the dead, dark outer bark (cork). The sapwood inside the cambium provides structural support, acts as food storage, and transports water from roots. The heartwood which is darker in colour compared to sapwood functions only as a mechanical support. (Knowpulp)

From the transverse section of the trunk of a pine we can learn something about the growth of the tree during its lifetime. The concentric circles, usually called annual rings but more accurately termed increment rings, originate in the alternating formation of fast-growing, thin-walled cells in the spring and summer, and slow-growing, small and thick-walled cells in late summer and autumn. On closer examination of rings in Scots pine (Figure 2.3) reveals a distinct two part structure. The inner lighter toned ring is that laid down during early spring growth, and is known as *"spring wood"*. This is relatively soft and the cells (tracheids) are thin walled and carry sap. The outer ring, sometimes being quite dark is usually a harder band and is laid in summer; it is called "*summer wood*". These tracheids are thick walled and provide rigidity and stability to the bole. The change from the thin wall to the thick wall tracheid can be very rapid as in Douglas fir, or more gradual as in Scots pine. Other softwoods such as the firs, spruces etc., display growth rings which are not so distinct, because the summer wood is pale. (Microscopy U.K. 2010)

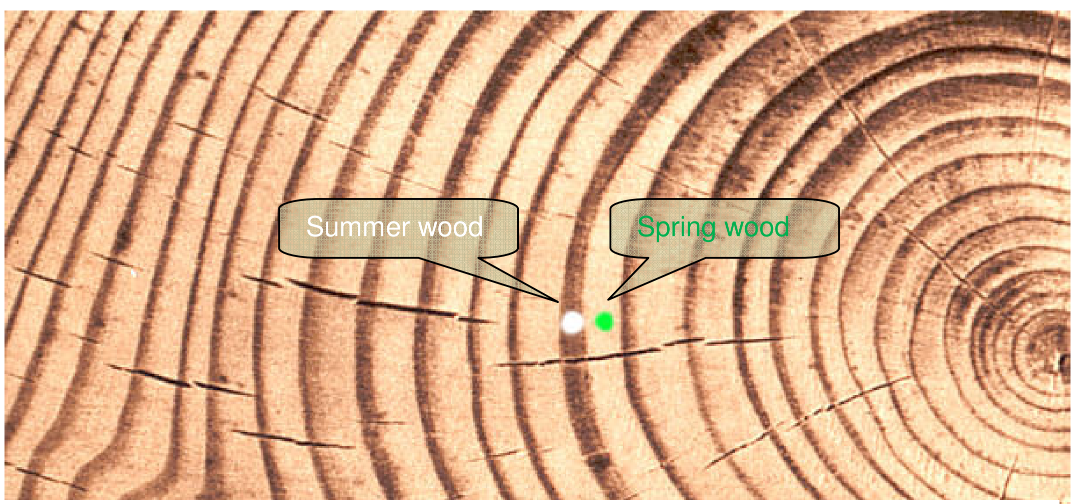

Figure 2.3 Scots Pine *(Pinus sylvestris)* x3 .Transverse section represents 30 years of even growth. (Microscopy U.K. 2010)

It could be noticed in above figure 2.3 that the summer wood and spring wood have different relative thickness depending upon weather conditions that year. The tree's age can be calculated by counting the number of annual rings.

2.4 Chemical composition of pine

Cellulose, hemicelluloses and lignin are the main constituents of wood. In different wood species, their relative composition varies greatly. Apart from above mentioned three compounds, wood also contains extractives, such as resin. Extractives are removed, to larger extent, in chemical pulping process. (Sixta 2006)

2.4.1 Cellulose

Cellulose is the main constituent of wood carbohydrates. It is a polysaccharide consisting of glucose units. The cellulose molecule easily forms hydrogen bonds with neighbouring molecules, thus giving xylem cells mechanical support. As it can be seen in table 2.1, Scots pine contains 40% cellulose (Knowpulp).

In terms of quantity, cellulose is the most abundant renewable polymer resource available worldwide. It has been estimated that, by photosynthesis 10^{11} to 10^{12} tons are synthesized annually in a rather pure form (e.g., in seed hairs of the cotton plants), but mostly are combined with lignin and other polysaccharides (hemicelluloses) in the cell wall of woody plants. (Klemm, Schmauder & Heinze 2002, pp.277-319)

Table 2.2 Chemical composition of some typical cellulose-containing materials (Sixta 2006, p. 24)

Source	Composition[%] cellulose	Hemicelluloses	Lignin	Extract
Hardwood	43-47	25-35	16-24	2-8
Softwood	40-44	25-29	25-31	1-5
Bagasse	40	30	20	10
Cotton	95	2	1	0.4
Hemp	70	22	6	2
Jute	71	14	13	2
Wheat straw	30	50	15	5

As it could be seen from the above table 2.2, other cellulose-containing material includes agricultural residues, water plants, grasses, and other plants' substances. Whereas, commercial cellulose production concentrates on the harvested source such as wood or on naturally highly pure sources as cotton.

2.4.2 Hemicelluloses

Hemicelluloses are heteropolysaccharides, and differ from cellulose in that they consist of several sugar moieties, are mostly branched, and have lower molecular masses with a DP of 50...200. Hemicelluloses play a crucial role in the bonding capacity of fibres, i.e. the ability to form interfibre bonds, which gives the paper fibre network its strength. A considerable percentage of the hemicelluloses dissolve in the production of chemical pulp. Hemicelluloses comprise 26% in case of pine. (Sixta 2006, p. 28)

2.4.3 Lignin

Lignin is a natural multibranched polymer, whose purpose is to bind fibres tightly to one another inside the wood, thus providing strength. Even though the lignin concentration is highest in the intermediate lamella between fibres, lignin is also found throughout the fibre cell wall. Unlike cellulose and hemicellulose, lignin is a hydrophobic substance. As a result, lignin molecules do not easily form bonds with one another to reinforce the fibre network in the paper. It is lignin that gives native wood its colour. Scots pine contains 27.7% lignin, whereas the amount of lignin in softwood ranges from 25-32%. (Knowpulp; Gullichsen & Fogelholm 2000)

2.4.4 Extractives

In addition to its major structural components, cellulose, hemicelluloses and lignin, wood contains also an exceedingly large number of other low and high molecular weight (organic) compounds, the so-called accessory compounds or extractives. The content of accessory content compounds in the wood of tree from temperate zones amounts approximately 2 to 5 %, but the concentration can be much higher in certain parts of tree, for example, the branches' bases, heartwood and roots. Relatively high amounts (up to 20% of dry matter) of extractives are found in certain tropical and subtropical woods. (Sixta 2006, pp.33-35)

The content and composition of extractives not only vary among the wood species but also with the geographical site and season. This fact is important for the production of pulp as certain extractives in fresh woods may cause yellow discolorations (pitch troubles) or a yellowing of the pulp. In addition, extractives may also influence the strength of refiner pulp, the gluing and finishing of wood as well as the drying behaviour. The percentages of the extractives in the sap- and heartwood of *pinus sylvestris* could be seen in table 2.3. (ibid)

Table 2.3 Percentage of the extractives in the sap- and heartwood of pinus sylvestris (based on dry wood). (Sixta 2006, p.35)

	Sapwood	**Heartwood**
Petroleum ether	2.20	8.80
Ether	0.06	0.80
Acetone/water(9/1)	0.30	0.70
Ethanol/water	0.40	0.40

As it could be seen from the above table 2.3, the amount of extractive is not equally distributed within wood. They are rich in roots and heartwood, but less on other parts of tree. The amount and type of extractive varies with species. According to Torgnysdotter (2006), despite their small amounts, the presence of extractives may seriously interfere with papermaking.

3 COMPARISON OF PINUS SYLVESTRIS WITH BETULA PENDULA AND EUCALYPTUS GRANDIS

3.1 General

Pinus sylvestris which is commonly known as Scots pine is softwood species, whereas *Betula Pendula* (Silver birch) and *Eucalyptus grandis* (eucalyptus) are hardwood species. Hardwood (deciduous trees, such as birch and eucalyptus) have more complex structure than softwood (coniferous tree, such as pine).

Mainly, fibre dimensions have a greater impact on the differences between softwood and hardwood pulps than chemical composition. Fibre length greatly affects the strength properties of the pulp and the paper made from it. On the other hand fibre width and fibre wall thickness affect fibre flexibility and tendency to collapse in the paper production process and, in turn, the paper properties. Fibre size also has an impact on the number of fibres per unit of weight, which has an effect on, for example, paper formation and optical properties. (Levlin & Söderhjelm 1999)

Hardwood fibre is considerably shorter and thinner than the softwood fibres. Generally hardwood contains more cellulose and hemicellulose and less lignin than softwood, while the proportion of extractives, i.e. resin, is higher. The molecular mass of hardwood lignin is also apparently lower than softwood lignin.

3.2 Growth properties

In terms of growth, these 3 species are very different. Scots Pine plantation rotations vary between 50-120 years, with longer rotations in northeastern areas where growth is slower. For the Scandinavian pine, it takes about 75 years to be ready to harvest, compared to a pine in south USA where it only takes 25 years for the tree to be ready to harvest. This is due to the warm climate all year around. It has a dry density of around 470 kg/m^3 . (Karlsson 2006, p.11)

Birch is a naturally growing tree species, which is ready for logging in 30 - 60 years. To reach saw timber stage, it grows around 80 years. Birch is dense, with a specific gravity of approximately 500 kg/m^3. (Knowpulp)

Eucalyptus grandis (tropical variety) grows in plantations, in Brazil. The average cycle of forest under cultivation is about 14 years. First thinning of eucalyptus is from 4 to 5 years, harvesting from 7 to 8 years. Eucalyptus grandis has a lower density (500 kg/cm^3). (ibid)

3.3 Physical characteristics

If these species are compared according to their physical characterstics, Scots pine fibres are on average 3 mm long, 30 µm wide. Finnish birch wood fibres are on average 1.1-1.2 mm long, 18-22 µm wide. Fibre has relatively thin walls which means it collapses easily.Fiber length of eucalyptus is 0.95 mm and width 16 µm. Fines content is quite low. (Knowpulp; Nanko & Button & Hillman, 2005)

Table 3.1 Comparison among different species. (Karlsson 2006, p.84)

	Pine	**Birch**	**Eucalyptus**
Length [mm]	3	1.1-1.2	0.9-0.95
Width [µm]	30	18-22	12-16
Wall thickness [µm]	8	3	2-3
Number of fibres/mg	2000	8000	16000
S(m^2/g) at tensile index 50kNm/kg	29	34	41

As it could be seen from the table above, the amount of fibres per gram vary with large difference. These will affect surface properties of the end product manufactured.

Length is one of the most important characteristics of papermaking fibres. A long fibre can have more bonds with other fibres and therefore be more strongly held in the network than a short fibre. The tensile strength of wet web increases rapidly with fibre length. Tensile strength, breaking strain, and fracture toughness of a dry paper often also improve with increasing fibre length. (Niskanen 1998)

3.4 Process properties

Different species' ability to cook varies and so do the defibration point. The defibration point of eucalyptus is at kappa number 18, when it is for spruce approx. 40. Eucalyptus has a very high cellulose content and low hemicelluloses content, while in birch the exact opposite is true. This is why higher yields can be achieved with eucalyptus than birch. The yield of pine compared to birch and eucalyptus is low. Additionally, the wood from eucalyptus plantations is more uniform, thus it has better fibre quality and processability. (Knowpulp)

While washing, birch pulp is more difficult to wash than pine pulps, which is probably due to a difference in wood extractive composition and the better ability of birch pulp to retain water. The drainage of birch pulp is usually lower than for pine pulp because birch fibres are shorter and more flexible. Pine contains saponifiable extractives that cause foaming in pulp washing whereas birch and eucalyptus contain less extractive and do not arise much problem. Extractive content of eucalyptus is even less than half that of birch, so washability is better compared to birch but drainage can be very poor. In knot separation, for pine pulp typically 1-3 % of the main stream is removable fraction; for birch pulp it is usually smaller. Screening of eucalyptus pulp is even easier. (ibid)

Low fibre swelling is in correlation with good dimensional stability of paper. Eucalyptus fibres with low hemicelluloses content tend to swell less, hence providing good dimensional stability compared to birch and pine. (ibid)

3.5 Product properties

Long fibres of pine have good strength properties, mainly tensile and tearing strength, which provide excellent runnability in converting equipment (paper machine, coater and printing press). Birch and eucalyptus short fibres give paper a smooth printing surface, a more even sheet surface, better formation, smaller pore size and superior opacity. Because there is less lignin in birch and eucalyptus, compared to pine, it is also easier to bleach the pulp to higher brightness. The qualities make the fibres of these hardwood species suitable for use in printing paper, although this type of paper generally consists of a blend of hardwood and softwood pulp to meet both the strength and the printing surface demands of the customers. (Karlsson 2006, p.10)

As eucalyptus fibres are smaller than those of pine and birch fibers, their number per unit of weight is higher and additionally fibre distribution of eucalyptus is also relatively narrow which makes the pore distribution of paper narrower. This gives papers made with eucalyptus pulps better formation, good ink absorption ability and a higher degree of opacity than papers made from pine and birch pulps. In addition to that, eucalyptus' short and stiff fibres have low surface strength. As bulk and stiffness are crucial for board and non impact printing papers, eucalyptus has been found to be very suitable pulp for such cases. (Nanko & Button & Hillman 2005)

4 CHEMICAL PULPING

4.1 General

Pulping represents the process by which wood or other lignocellulosic material is reduced to fibrous mass, denoted as pulp. In chemical pulping, lignin is dissolved at elevated temperature (130-170℃), as fibres can be separated without any mechanical defibration only after 90% of the lignin has been removed. Unfortunately, delignification is not a selective process. Parallel to the lignin removal, significant part of hemicelluloses and some cellulose are degraded. The total fibre yield ranges from 45-55% (at a given extend of delignification of about 90%), depending on the wood sources and pulping process applied. In contrast, in mechanical pulping, the lignin bonding the fibres together is softened by heating the wood material through mechanical stress. Then, the fibre bonds are broken by means of mechanical stress and have an extremely high yield - over 90%, compared to chemical pulping process which is almost double. However, the strength properties of chemical pulps are overwhelmingly superior and can constantly be bleached to an extremely high brightness. In addition, chemical pulp mills that burn wood material dissolved in the process are self-sufficient in regard to electricity and steam power. These are the key reasons for production of pulp predominantly on global scale, by chemical processes. (Gullichsen & Fogelholm 2000; Sixta 2006, pp. 109-110)

Chemically separated fibres are flexible and have a high bonding potential. At the same time they are not much damaged and have kept their length in the separating process. They give strong paper. The main commercial chemical pulping techniques comprise the sulfate or Kraft, the acid sulfite, and the soda process. In 2000, the chemical pulps accounted for more than 77% of all wood based fibre material worldwide (see Table 4.1). (Sixta 2006, p. 110)

Table 4.1 Global pulp production by category in 2000. (Sixta 2006, p. 9)

Pulp category	Pulp production [Mio t]
Kraft	117.0
Sulfite	7.0
Semi-chemical	7.2
Mechanical	37.8
Non-wood	18.0
Recovered fibre	147.0

It could be seen from the table above that Kraft pulp production has the highest values among all, no matter if it is compared to mechanical pulp or within chemical pulps.

4.2 Kraft process

The principal method is the Kraft process (strongly alkaline, ~ pH14), which can be used with all kinds of wood. German chemist Carl F. Dahl invented the sulphate process in 1879. The process was called Kraft process, based on German and Swedish word for strength, as it produced stronger pulp at high yield. Kraft pulping has developed as the principle cooking process, accounting 89% of the chemical pulps and for over 62% of all virgin fibre material. In comparison, only 5.3% of the

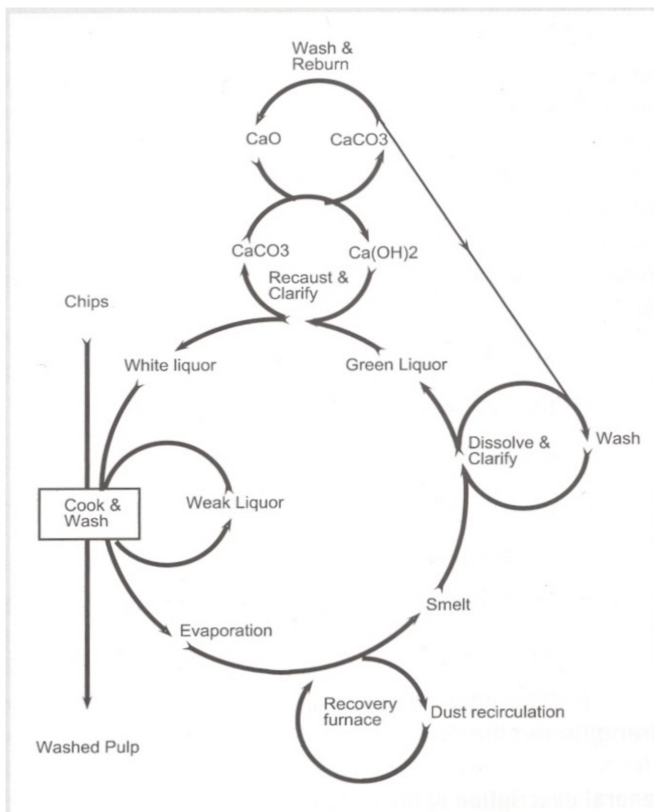

Figure 4.1 Simplified diagram of Kraft pulping's chemical recirculation loop. (Gullichsen & Fogelholm 2000)

world's chemical pulp production is obtained by the sulfite process. (Toland 2002, pp. 5-67)

The main active chemical agents in the Kraft process are hydroxide (OH^-) and hydrosulfide anions (HS^-) which are present in Kraft cooking liquor, as aqueous solution of caustic sodium hydroxide and sodium sulfide, denoted as white liquor. Other than these, white liquor also contains small amounts of Na_2CO_3, Na_2SO_4, $Na_2S_2O_2$, NaCl and $CaCO_3$ plus other accumulated salts and non-process elements. The hydro-sulfide ion plays an important role in Kraft pulping by accelerating delignification and rendering non-selective soda cooking into a selective delignification process. Delignification can be divided into three phases, namely the initial, bulk and residual or final phases. In the bulk delignification phase the main part of the lignin is removed while at the same time only minor carbohydrate losses occur. The point at which cooking is stopped depends on the pulp type being produced. In the production of unbleached pulp the final point is close to the defibration point. However, with continuous delignification, the dissolution of carbohydrates extensively increases. In order to maintain high yields and to preserve a sufficiently high quality of the pulp, delignification is limited to a certain degree of delignification, targeting kappa number of about 25-30 for softwood Kraft pulps. (Gullichsen & Fogelholm 2000; Sixta 2006)

The advantages of Kraft process are:

- Produces high strength pulp
- Handles wide variety of species
- Tolerates barks in the pulping process
- Cooking time is relatively short compared to other processes
- Regeneration of chemicals and energy is efficient
- Side-products such as turpentine and tall-oil are valuable

These factors, substantial technical development overtime and economical feasibility have further strengthened the position of Kraft pulping.

The main reaction variables in the alkaline cooking are wood species (i.e., their main chemical components), chips' dimensions, temperature, time, and the concentration of cooking chemicals. Some of the fibre strength differences are inherent in the wood species and their growing conditions, whereas other items are chemical and mechanical in nature. Most Kraft digesters are controlled by pulping to a constant H-factor. H-factor which indicates relative speed of lignin dissolution depends on cooking time and temperature. H-factor's dependency on temperature is very strong due to delignification temperature dependency. Even a difference of couple of a degrees in cooking temperature can make a big difference in pulp quality. H-factor has been defined so that 1 hour in 100 ℃ is equivalent with H-factor 1. As a rough rule of thumb, one can assume that the rate of reaction in Kraft pulping doubles with every 10°C increase in temperature. This pulping parameter is essentially a measure of thermal energy of the pulping process. A second aspect of this is the temperature profile of the cook. How fast the pulping process is brought to the target cooking temperature and how long the temperature is held is integrated into H-factor and pulping strategy. In addition to H-factor, the maximum cooking temperature and the alkali level of cooking liquor have a significant influence on fibre strength and the inherent bonding potential of the pulp. Most Kraft pulping operators have a target for the level of residual lignin (Kappa number) in the fibres exiting the digester. The variablility in kappa number is a measure of Kraft pulping uniformity. (Gullichsen & Fogelholm 2000; Nanko & Button & Hillman 2005; Sixta 2006)

The strength-bearing components of wood fibres are the cellulose molecules that aggregated into fibrils and fibril-aggregates with crystalline and amorphous regions. During chemical pulping, the fibre strength increases with the celluloses content up to certain level, after which cellulose degradation reactions become too severe, which in turn leads to a decrease in fibre strength. (Torgnysdotter 2006)

5 BEATING AND ITS EFFECT ON FIBRE PROPERTIES

Beating is used to enhance the binding power of plant fibres in paper sheets, which is done by applying mechanical stress to fibre as it is milled by a device called a “beater”. By performing such mechanical treatment, the fibre wall is squeezed, kneaded and plasticized, and the fibre surface is partly disintegrated. Mechanical shear separates parts of cellulose fibrils so that the fibre structure becomes hairy and fluffy. Fibrils may involuntarily be completely liberated from the fibre material, and some fibres may even be completely torn to fibre fragments. (Sixta 2006, p.1281).

Figure 5.1 Fibres before beating (Knowpulp)

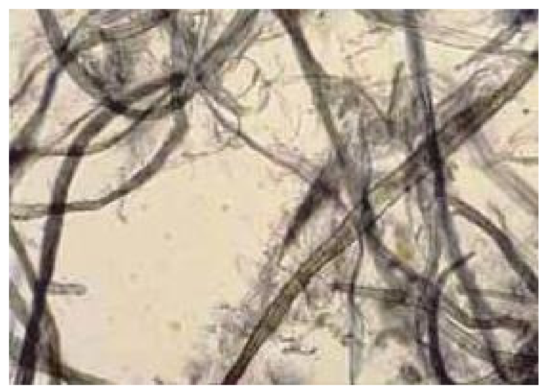

Figure 5.2 Fibres after beating (Knowpulp)

As it could be seen in the figures (5.1 and 5.2) above, beating changes several single fibre properties. The classification of primary structural effects on fibres can be internal fibrillation, external fibrillation, fines formation, fibre cutting, and straightening of fibres. Internal fibrillation increases fibre swelling and flexibility by “loosening” the cell wall structure, and external fibrillation increases the outer surface of fibre. The structure and bonding of paper depends on fibre properties such as fibrillation and also the density and tensile strength of paper therefore increase due to beating. There are indications that fibre/fibre joint strength also increases with beating due to changes in the physical structure of the fibre surface that makes new surfaces available of molecular bonding. Torgnysdotter, Page et al. measured the microscopic contact area of chemical pulp fibres and found an increase in the degree of bonding with beating. Fibrillar fines are produced during beating, which enhances the fibre/fibre joint strength and paper strength. (Levlin & Söderhjelm 1999, p. 41; Torgnysdotter 2006, p.25).

According to Niskanen (1998) chemical pulp is usually beaten to optimize its contribution to the mechanical properties of paper. Beating serves the purpose of increasing the area of contact between the fibres by increasing their surface through fibrillation and by making them more flexible. (Raymond & Rowell 1986, pp. 104-108).

Pulping and beating also affect the degree of swelling by altering the pore structure and the inherent network strength of the fibre wall. The moisture content of the fibres is greatly affected by their chemical composition, regarding which fibre charge is an important parameter. Different pulping techniques result in different chemical compositions of the fibre wall. By chemically increasing the total fibre charge, increased fibre swelling can be achieved. The charges most commonly originate from the carboxylic and sulphonic acid groups. (Torgnysdotter 2006)

In the chemical pulps, the amount of fines is lower than in mechanical pulps. There are two types of chemical pulp fines, the primary fines and secondary fines. Primary fines are present in unbeaten pulps. They contain parenchyma cells from the wood. Beating creates secondary fines. These include lamellar and fibrillar parts of the fibre wall and colloidal materials. The primary fines content of chemical pulp is typically less than 2%, but beating can increase the total fines content to 15%. Fines have large specific surface area because of the small particle size. Beating increases the surface area further. Because of their large surface area, fines improve bonding between fibres. In paper, most fines surface is bonded to fibres when paper dries. Particularly chemical pulp fines bond almost completely, and essentially all the free surface is lost. (Niskanen 1998, pp.63-64)

The major effect of beating is a drastic increase of water uptake by the fibre material. The kneaded cell wall will swell, and the fibril fur on the surface will store water by capillary forces, while the isolated cellulose fibrils aggregate to hydro gels containing huge amount of immobilized water. The hydrodynamics volume of the fibres is increased substantially, so that filtration as in sheet forming process is severely hampered. This effect is used to characterize the effectiveness of beating, by measuring drainability. On the other hand, beating lowers the drainage capability of pulp and this reduces the production rate and increases the energy consumption. Some paper properties are improved with beating but others deteriorate. (Sixta 2006, p.1281)

Beating increases most of the strength properties of the paper except tear strength, which increases with gentle beating but drastically decreases with more intense beating. The internal fibrillation arising from the beating makes the fibre more flexible and densifies the sheet during drying, increasing the total bound area of the sheet. An important effect of beating is the straightening of fibres. (Torgnysdotter 2006, p.25)

Figure 5.3 PFI mill

Laboratory beating simulates the industrial beating process to predict the usability of a pulp. Since beating has a large influence on the pulp properties, beating in the chemical pulp testing is possibly the most important single phase. This includes the amount of beating energy and the beating intensity, since both significantly influence pulp and sheet properties. Any changes in the single fibre properties also change the corresponding pulp and paper quality. For example, pulp drainage resistance increases due to an increase surface area (mainly fines formation) during beating. (Levlin & Söderhjelm 1999, p. 41) The optimum beating conditions must be determined case-by-case to meet the end-product requirements coupled with the mill-specific conditions. (Kcl, 2010)

As an example of influence of the amount of beating on the properties of paper, the tensile strength increases but the opacity decreases. Here the amount of beating is a critical control variable to gain our desired product, as the tensile strength and opacity both are important properties for the paper. (Levlin & Söderhjelm 1999, p.13)

Lindström has reviewed the chemical factors influencing the behaviour of fibres. The quality of water used has a significant effect on the pulp behaviour and therefore on the beating results. Important water parameters are pH, electrolyte content and temperature. All these influence the swelling of fibres. (Lindström & Kolman 1982)

6 EXPERIMENTAL PART

6.1 Experimental design and methods used

Two different pine Kraft pulps were pulped in laboratory scale using a liquid circulation batch process. The initial plan was to achieve two different pulps, one with high kappa (~30) and the other with low kappa (~20). When the pulps with low lignin content (kappa number 18.4) and the other with high lignin content (kappa number 28.5) were achieved after several cooking trials, then further work was proceeded. Both of them were beaten to four different revolution degrees in PFI mill. Later hand sheets were prepared from the pulps beaten at different degree and unbeaten pulp. Different pulp properties were measured from each beaten pulp fraction and the unbeaten pulp, obtained from both cookings and later handsheets were prepared from each fraction. The parameters of the experimental setup are put together in table 6.1.

Table 6.1 Parameters of the experimental design.

Plan	Target	Achieved
2 different cookings	Low lignin content (Kappa number: ~20) and High lignin content (Kappa number: ~30)	Low lignin content (Kappa number: 18.4) and High lignin content (Kappa number: 28.5)
4 degrees of beating	1000, 2000, 3000, 4000	1000, 2000, 3000, 4000

As shown in the above table, two different cookings were planned to achieve the target. The required pulps were obtained after adjusting few important parameters which affects the cooking process, such as H- factor, amount of active alkali [g^{NaOH} /l], temperature profile of cooking and duration of cooking.

6.2 Raw material

Fresh pine chips were fetched from the Stora Enso, Kaukopää mill, Imatra for all required cookings. The moisture content of the chips used in cooking was different in two different cooks. To preserve the moisture content of chips, it was kept in the refrigerator at temperature 5 ºC. Later, the chips were screened in Gyratory screen. An even distribution of chip size improves the quality of the pulp and also improves defibration speed and production, which was the reason why only the chips within 19 mm – 25 mm length were used in the pulping process. Barks, knots and fines were also completely removed during the chip screening, as they were not suitable for the pulping process. The white liquor used in the cooks was also brought from Stora Enso, Kaukopää mill, Imatra.

6.3 Cooking method and conditions

Cooking was done in a liquid circulated laboratory batch digester of tank size 0.010 m^3 (10 litres). Liquid was circulated between heat exchanger and digester tank continuously increasing the temperature of liquid, as it was heated by heat exchanger which was operated by electricity. Although the system can reach maximum temperature up to 171 °C and stand up to 20 bars pressure, only 9 bars was reached as maximum pressure and temperature was 170°C during operation. For each cooking ~1000 g of oven-dry screened chips were used. The cooking was done in alkali conditions as white liquor was used in cooking process. The amount of white liquor required was calculated. The active alkali was 141 [g^{NaOH} /l] of white liquor used for the cooking process and sulfidity was 35%.

First of all, the chips were fed into the digester tank, and then a measured volume of white liquor was poured. Required amount of water was added to maintain wood to liquid ratio, which was 1/4. In each cooking, 90 minutes were used to raise the temperature of cooking liquor from 80°C to 170°C. The idea was to increase heat quite slowly (~1°C /min) providing enough time for impregnation, so that the chips get homogeneously cooked. Cooking was done for 79 minutes at 170 ℃. The pulp received from the cook had kappa number 28.5. The amount of active alkali percentage for the high kappa cooking was 26% from the oven-dry wood. In the next cook, cooking time was extended to 110 minutes to get a low kappa number and the amount of active alkali percentage was increased from 26% to 30%. After each cook, ~100 ml of black liquor was collected to analyse residual alkali content. The black liquor inside the tank was let to cool down by switching off the heater and opening the cold water supply to heat exchanger. Pulp was washed, as temperature reached 50ºC and pressure was below 1.5 bars. For washing, warm water was injected to digester tank and wash outlet was flown to drainage. Use of warm water while washing was necessary, so that the pulp quality remained as stable as possible. After washing for 10 minutes inside the tank, cooked chips were taken out and were further washed.

6.4 Disintegration and screening

As the cooked pulp was like fibre bundles loosely packed, it was necessary to separate them with mechanical treatment. The pulp was disintegrated in a disintegrator. Disintegrated pulp was screened in Somerville screen with the slots of diameter 0.20 mm. The accept and reject pulps from the screening were collected separately in two different cotton bags. The bags were centrifuged to remove as much water as possible, so the degradation of fibres during long storage time will slow down. Later the accept pulp was transferred to an air tight container and was kept inside the refrigerator at 5 ºC. Generally, accept pulps were stored for maximum of 2 weeks while they were being used in the experiment. The moisture content and weight of shives (reject) were measured and then shives were thrown away.

6.5 Kappa analysis

The kappa number is an indication of the lignin content (hardness) or bleachability of pulp. For the analysis, 2g of oven-dry pulp was taken as sample. Three trials were made for each pulp category and kappa number was calculated. An average was taken from calculated trials. The average kappa numbers obtained were 18.4 and 28.5 for low and high lignin contained pulp respectively. Kappa number was measured following the standard procedure stated in ISO 302-1981(E).

6.6 Residual alkali measurement

Residual alkali test shows the amount of alkali remaining in the black liquor, after the cooking was finished. Two different samples from each cooking were titrated till the alkalinity dropped down to the pH 10.5 and the amount of hydrochloric acid (HCl) consumed during the titration was noted. Those measured values were the residual alkali content in the pulp. The values are given in the appendix 3. All the procedures followed during this test were according to ISO 699:1982(E).

6.7 Beating

The accept pulp received after screening was beaten in PFI mill. A measured amount of pulp of specified stock concentration was beaten between a roll with bar and a smooth beater housing, both rotating in the same direction, but at a different peripheral speeds. The main part of the beating energy transfers to the pulp via bar surface not via the edges. In PFI, the beating consistency was high, 10% compared with a normal low consistency beating of about 2%-5% in paper mills.

For beating, 30±0.5 g of oven-dry pulp at 10% consistency was taken. Sample pulps were beaten to 1000, 2000, 3000, 4000 revolutions. After beating there were 4 different types of beaten pulps and an unbeaten pulp (control) category from each cooking. The work was done following the standard procedure stated by ISO 5264/2-1979(E).

All the further experiments were continued with these five pulp categories.

6.8 Pulp properties test

The drainability of a pulp suspension in water (Schopper-Riegler number), fibre length and water retention value (WRV) were measured from each pulp category. The standard procedures followed for tests are listed in appendix 4.

6.9 Handsheet preparation

Laboratory hand sheets were prepared using “Rapid-Köthen” sheet former. Hand sheets of basis weight $80 g/m^2$ were made. Five sheets from each category were taken, which were within ±3% range of $80 g/m^2$. There were total 50 accepted sheets (5 sheets x 10 categories). These sheets were later used to test different paper properties. The standard procedure followed for handsheet preparation was ISO 5269-1:1998(E).

6.10 Handsheet tests

Optical properties and strength properties were measured from the sheets. The following strength properties were measured from the sheets.

- Tensile strength
- Tearing strength
- Thickness
- Bursting strength
- Air permeability.

And optical properties were

- Brightness
- Opacity

7 RESULTS AND DISCUSSION

Results received from the experiments are illustrated in charts. Explanation below each chart explains the change occurred after each beating. Though, only the key points are explained, a lot more can be analyzed from the chart and in addition to that detail values could be found in appendices. The unbeaten or control pulp and control paper sheets are taken as reference for comparison.

7.1 Comparison between low and high lignin contained pulp of pine

The yield was 42% for the pulp with kappa number 28.5 whereas it was even less, 38% for the pulp with kappa number 18.4. Typically, it was normal to get smaller yields for the later one as the cooking time was extended to dissolve as much lignin as possible, where cellulose and hemicelluloses dissolved too. The amount of active alkali per gram oven-dry wood for the high kappa cooking was 26%, whereas for the low kappa cooking it was 30%. In addition to that, disintegration performed prior to pulp screening to separate fibres had significant effect, especially in case of high kappa pulp which could be seen throughout the result.

Schopper-Riegler measurement

The international standard specified method for determination of the drainability of a pulp suspension in the water is described with the term Schopper-Riegler (SR) number. It is designed to provide a measure of the rate at which a dilute suspension of pulp may be dewatered. As the drainability is related to the surface conditions and swelling of the fibres, and constitutes a useful index of the amount of surface treatment to which the pulp has been subjected.

Ordinary laboratory apparatus was used during the measurement, which consists of a measuring cylinder with a scale. The scale on which a discharge of 1000 ml corresponds to a SR number of zero and zero discharge to SR number of 100. The tests were preformed following the procedures strictly stated on ISO 5267/1-1979 (E). All the values from the tests are given in appendix 1, table 1.

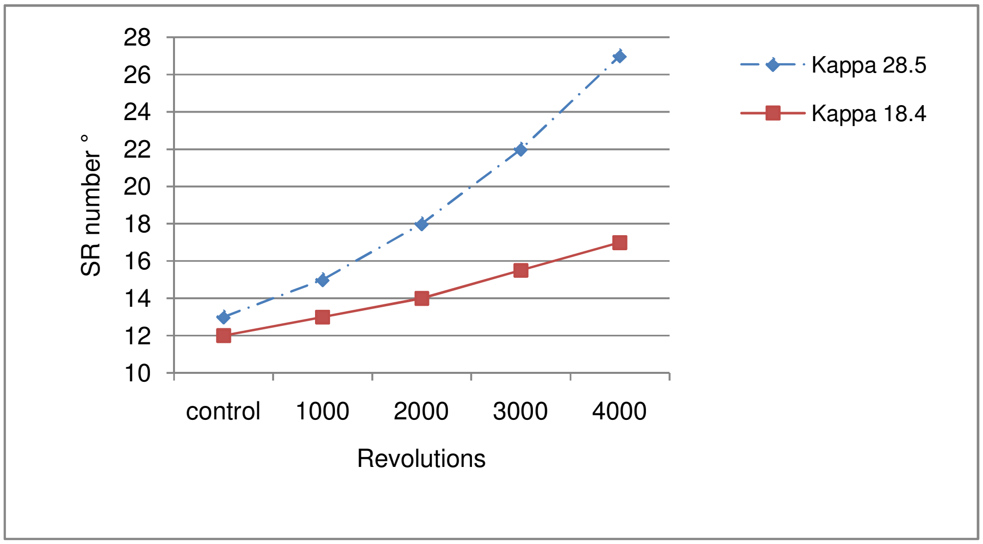

Chart 7.1 Sr number versus revolutions in PFI mill

In above chart, Sr number versus revolution, SR numbers increased by 8.4% and 15.4% respectively for low and high lignin containing pulps at first beating. The values increased sharply after 2000 revolutions as slope could be noticed where increment was highest, 11% and 22% for low and high lignin containing pulps. Overall increment in Sr number after beating 4000 revolutions in PFI mill compared to unbeaten pulp was 42% and 108% for low and high lignin containing pulps respectively.

As an important remark, SR number for low kappa was considerably lower than in other pulps around the same kappa number. This may be due to error in device, which remained unnoticed but it is uncertain to some extent. In addition another possibility may be that pulp with lower lignin content may have slower response to beating compared to higher one. For the most pulps tested, properties were in agreement with previous studies found in the literature.

Fibre length

Fibre length was measured using “Kajaani FS 300 Analyzer” to measure the effect of increasing amount of beating on the single fibre. From each pulp category, 3 measurements were taken with same conditions and sample amount and an average of them was taken into account. The values of fibre length analysis are given in appendix 1, under the table 2.

Fibre length of high lignin containing pulp seems to be quite short compared to low lignin containing pulp. As a matter of fact, it was due to difference in raw material used. As the raw material was fetched for each cooking, it is possible that both raw materials may not have same characteristics when compared on microscopic level. So that may be the reason for long fibres in case of low lignin containing pulp but not in the high lignin containing pulp.

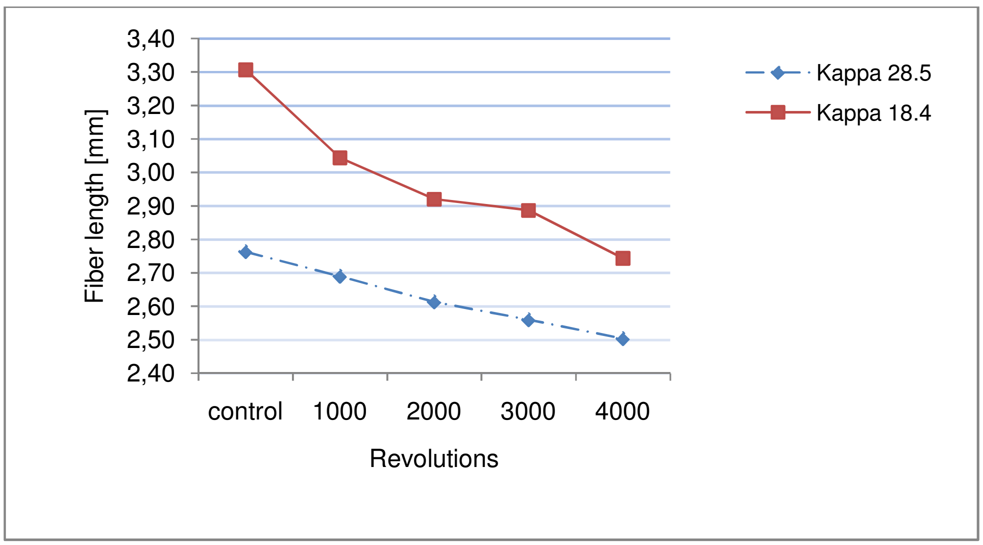

Chart 7.2 Fibre lengths versus revolutions in PFI mill

Fibre length decreased with the increasing number of revolutions which may be the result of fibre breakage while beating. Although the differences were small, it provides the proof of fibre breaking and creation of secondary fines while performing beating in PFI mill. The maximum decrease in fibre length was 8% at first beating of low lignin containing pulp. In totality, fibre length decreased by 17% and 10% after 4000 revolutions compared to unbeaten fibres for low and high lignin containing pulps respectively.

The fibre length of high lignin containing pulp was smaller compared to the low lignin containing pulp which affected the overall results.

Water retention values

Water retention value (WRV) describes the amount of water remaining in a wet pulp sample after centrifuging. It is the ratio of water to dry fibre weight. Water retention provides better information of how beating response on fibres and water removal at press section than CSF or SR. It depends on parameters such as salt content, pH, and temperature. WRV has been reported to be an indicator of fibre flexibility and swelling too. The values of water retention are given in appendix 1, under table 3.

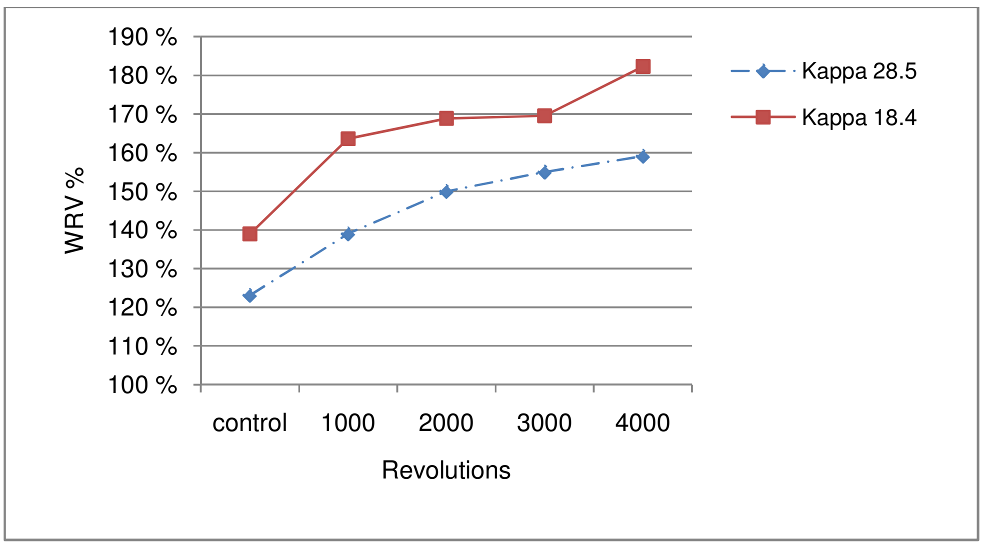

Chart 7.3 Water retention value versus revolutions in PFI mill

As a matter of fact, pulp with less lignin content had initial WRV 139% and pulp with high lignin content had 123% before any mechanical treatment. After beating both pulps to 1000 revolutions in PFI mill, there was a drastic increase of water uptake by the fibre material in both cases. In further beatings, increments were 7% at maximum for both low and high lignin containing pulps.

Tensile strength

Tensile strength is a very important property to describe the general strength of paper. The tensile index value relates strength to the amount of material being loaded. Tensile index therefore has primary use to describe the strength of pulps. Tensile strength was measured using “Testometric Micro 350”. A sample of 15 mm width and 18-20 cm length was used for the tests. The values of tensile strength shown as tensile index are given in appendix 1, under the table 4.

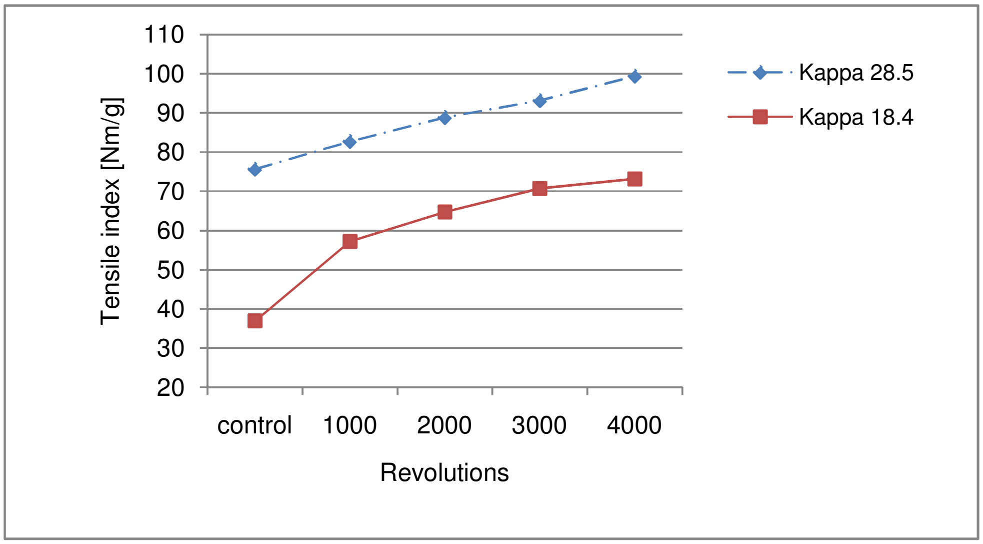

Chart 7.4 Tensile index versus revolutions in PFI mill

As Chart 7.4 demonstrates, the effect of beating improved paper tensile strength properties by 55%, 13%, 9% and 3.5% after 1000, 2000, 3000 and 4000 revolutions in case of low lignin contained pulp. The results for high lignin contained pulp were 9.4%, 7.4%, 5%, and 7% at 1000, 2000, 3000 and 4000 revolutions in PFI mill. The increased amount of beating respectively increased paper tensile strength. There was a significant increase in paper strength, when comparing beaten fibers to unbeaten (control) fibers.

In general, tensile strength continuously increased from the unbeaten pulp to highly beaten one in both pulp categories. A sharp increase in the tensile index, 55% could be seen in low kappa pulp, whereas for high kappa pulp tensile index increased only by 9%, after 1000 revolutions in PFI mill. In addition to that the tensile strength for low kappa was much lower then expected.

Tear strength

The tear strength measures the ability of the sheet to resist the propagation of a tear. The tear strength is truly a measure of the amount of energy required to fracture a sample. A rule of thumb is that as tear strength decreases the tensile strength increases. In the experiment, tearing strength was measured using "DIGI-TEAR", a device produced by Messmer muchel. A sample of 62 mm length and 50 mm width was used for the measurement. The values of tearing strength are shown as tear index in appendix 1, table 5.

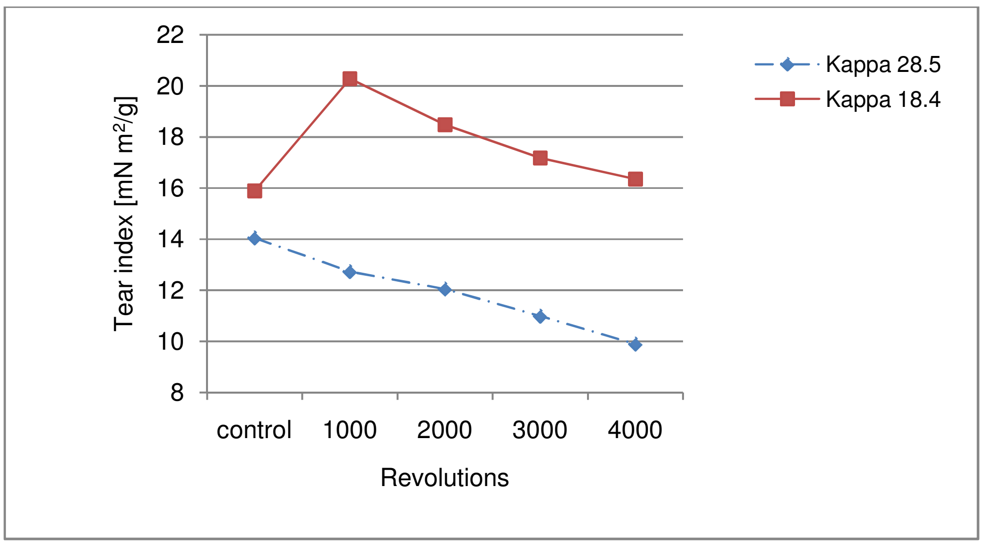

Chart 7.5 Tear index versus revolutions in PFI mill

The behaviour of tear index as we can see from the above chart, increased sharply at the first beating by 28% for low lignin containing pulp then it gradually decreased. The behaviour of high kappa was unusual as it was supposed to increase to certain amount and then decrease, but it decreased steadily from the very first beating.

Burst strength

Burst strength is the maximum pressure that the paper can resist without breaking with pressure applied perpendicular to the plane of the test piece. Bursting strength was measured using the “Lorentzen & Wettre - Burst-o-matic”, a burst strength measurement device. Five measurements were taken from each sample, at 1606 kPa. Burst index can be found plotted below. The values of bursting strength shown as burst index are given in appendix 1, table 6.

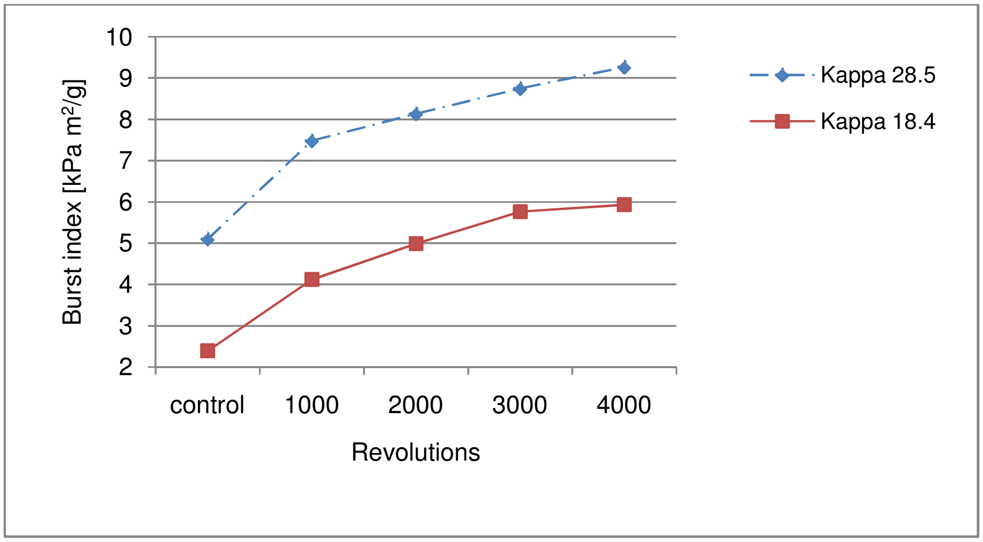

Chart 7.6 Burst index versus revolutions in PFI mill

Burst index increased by 72% and 47% for low and high lignin containing pulps respectively, which was the major increment after 1000 revolutions in PFI mill. In totality, burst index increased by 148% and 82% after 4000 revolutions compared to unbeaten fibres for low and high lignin containing pulps respectively.

In general, the bursting strength of high lignin containing pulp seems to be better which is obvious as the cooking time was 30 minutes less compared to low lignin containing pulp, so the degradation of cellulose and hemicelluloses is lower.

Bulk

The actual, physical thickness of a piece of paper, usually expressed in thousandths of an inch, is the bulk of the paper. Bulk affects the flexibility of paper. Thickness of sheets was measured, so that the bulk of sheet could be calculated. The measurement was taken from 6 different locations on the sheet using the “L&W Micrometer 51”. The average thickness of each sheet was calculated. Then, the bulk was calculated for each sheet. The values of bulk are given in appendix 1, table 7.

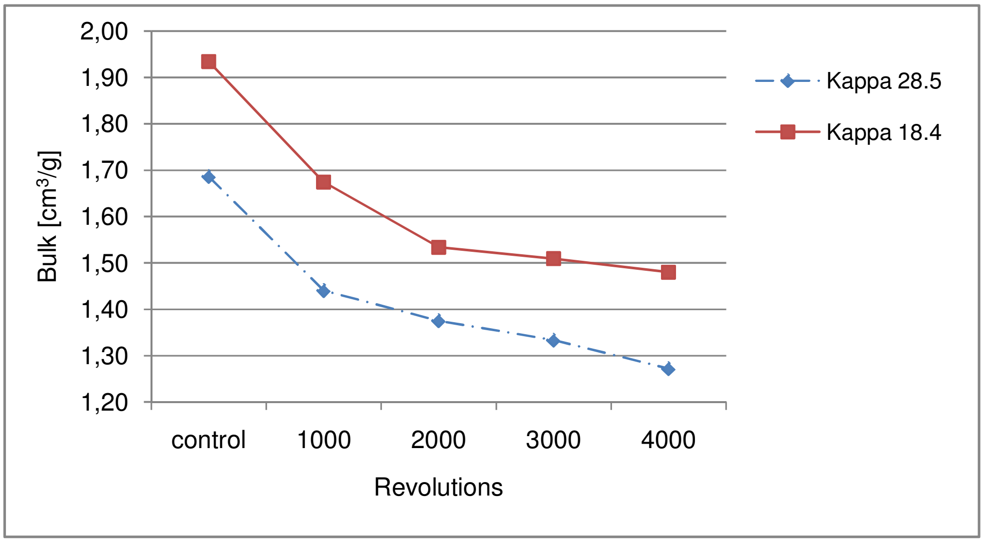

Chart 7.7 Bulk versus revolutions in PFI mill

In general, bulk decreased continuously with the increased amount of beating. It decreased by 14% and 15% for low and high lignin containing pulps respectively which were the highest decrements in both categories at first beating. Overall bulk decreased by 24% and 23% for low and high lignin containing pulps respectively after beating 4000 revolutions in PFI mill compared to unbeaten pulps.

The sheets made from high lignin containing pulp were supposed to have higher bulk compared to the sheets made from the pulp with low lignin containing pulps, but quite surprisingly the values were opposite. The pulp with high lignin containing pulp had lower bulk. As the fibre lengths of raw materials were different, it may have affected the bulk.

Air permeability

If the air-permeability of the paper is too high, it means that paper is porous. As an effect of beating, paper produced will be less porous and properties such as density, strength, or smoothness will increase to certain extent. Air permeability was measured using the “MBT- Permeance Tester”, a device produced by Messmer instrument limited. Measurements were done using pressure 0.74 kpa and values are expressed in terms of Bendtsen ml/min. The values of air permeability are given in appendix 1, table 8.

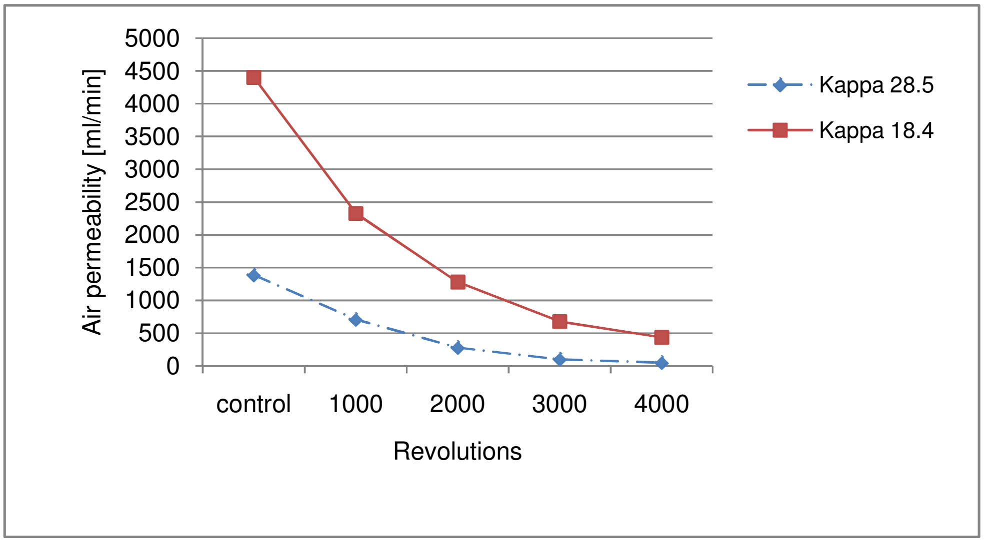

Chart 7.8 Air permeability versus revolutions in PFI mill

Chart 7.8 shows the air permeability change before and after beatings. As expected, after each beating stage the air permeability decreased to certain level as the paper became less porous. With increasing amount of beating, the bondability between the fibers enhances and paper density increases which results as dense and smooth paper. High air permeability, more than 2000 ml/min could be result of mainly coarse fibers and a relatively low level of primary and secondary fines which could be noticed in low lignin containing pulp in case of unbeaten and beaten up to 1000 revolutions in PFI mill.

Air permeability was suppose to be higher for high lignin containing pulp as fibres were stiffer in comparison to low lignin containing pulp. But the high lignin containing pulp had dense formation which directly affected the air permeance. Due to the reason, the air permeance of high kappa pulp was lower than low kappa pulp.

Optical properties

Opacity and brightness are most important reflectance values of paper. Opacity characterizes the ability of paper to hide text or pictures on the back side of the sheet. Brightness is reflectance of paper using blue light. Blue light is used because papermaking fibres have a yellowish colour and because the human eye perceives blue colour as brightness. “Lorentzen & Wettre – Elrepho” was used to measure optical properties.

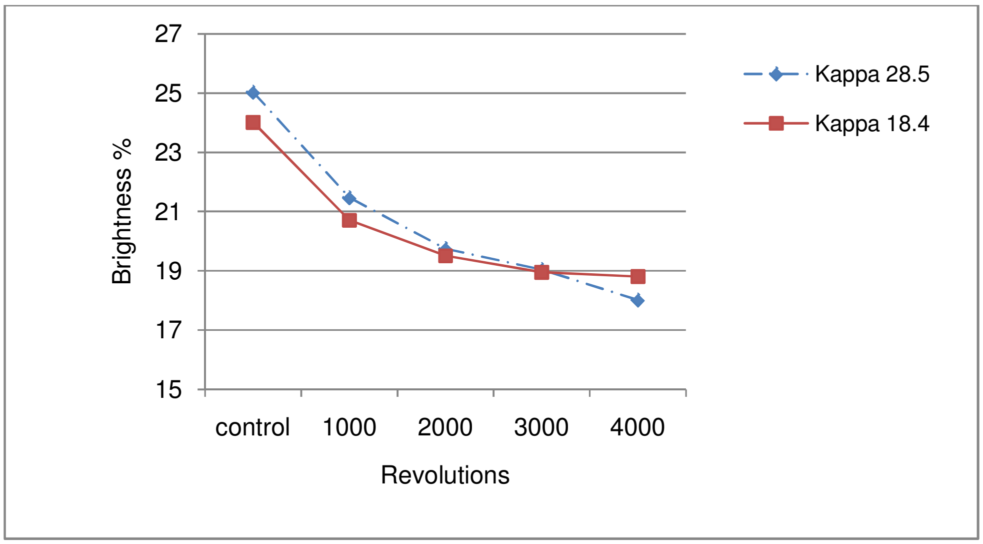

Chart 7.9 ISO Brightness versus revolutions in PFI mill

As can be seen from the Chart 7.9, the brightness value decreased sharply by around 14% for both low and high lignin containing pulps after the first beating, whereas it decreased slowly after first beating in low lignin containing pulp and stopped at final brightness of 19%. But brightness value for the pulp with high lignin content decreased quite huge compared to low lignin containing pulp. The overall brightness was decreased by 22% and 28% for low and high lignin containing pulps respectively after beating 4000 revolutions in PFI mill compared to unbeaten pulps. The values of brightness are given in appendix 1, table 9.

In optical properties no major differences between high and low kappa pulp were observed. The brightness decreased with increasing amount of beating in both cases.

7.2 Comparison of different properties among pine, birch and eucalyptus

In this section, all the values from the experiments made during this thesis work are compared with the results from the earlier thesis work done on birch and eucalyptus. The comparison is made for all the results which were obtained from the earlier thesis work done by Pyykkönen in year 2008.

Comparison of Schopper-Riegler values

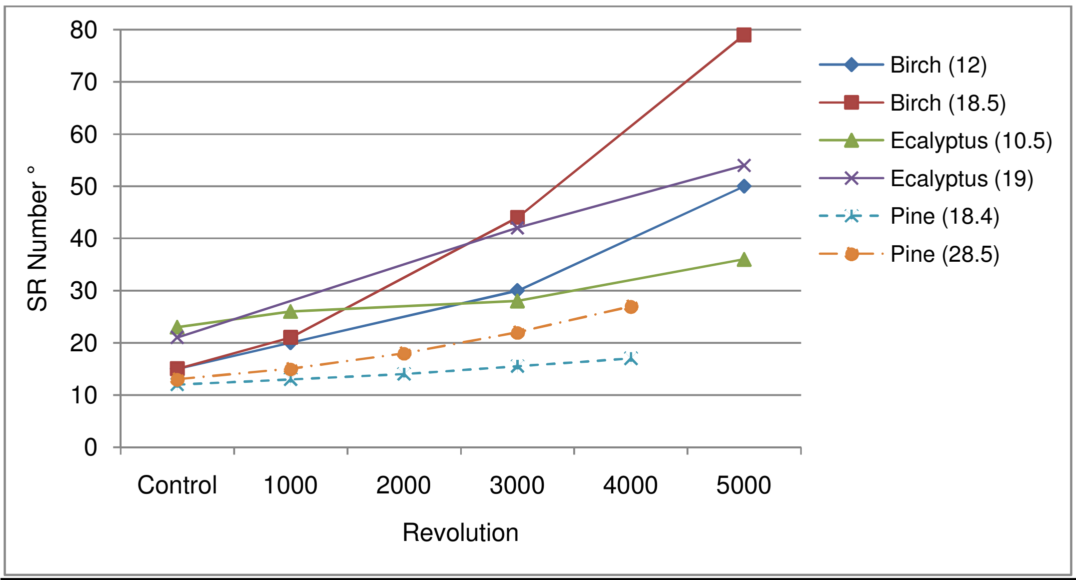

Chart 7.10 Sr number versus number of revolutions in PFI mill

Birch with high lignin content has the highest increment in Sr number by 426% which is followed by birch with low lignin content 233% which were the values for unbeaten and beaten up to 5000 revolution. For eucalyptus, Sr number has increased by 157% and 56% for high and low lignin content pulps respectively after 5000 revolutions, but in case of pine, the increments were very low. For pine with high lignin content Sr increment was 108% whereas for low lignin content it was even less then that, 42%.

It may be caused by the short fibres of birch, that birch fibres cannot form dense fibre web on wire, as orientation of fibres is poor for short fibres and that lets huge amount of water pass through the wire, which increases more when the fibres are beaten. Same phenomena will explain the relatively high drainability of eucalyptus fibres too, whereas pine acquired lowest SR number as it had longest fibres among all. The fines generated from the beating did not affect much as in the earlier cases where the initial fibres were shorter. If we consider the initial fibre lengths, pine has nearly 3 times longer fibres than others, so the drainability was low for pine. (Values for the above chart are available in appendix 2, table 1).

Comparison of fibre length

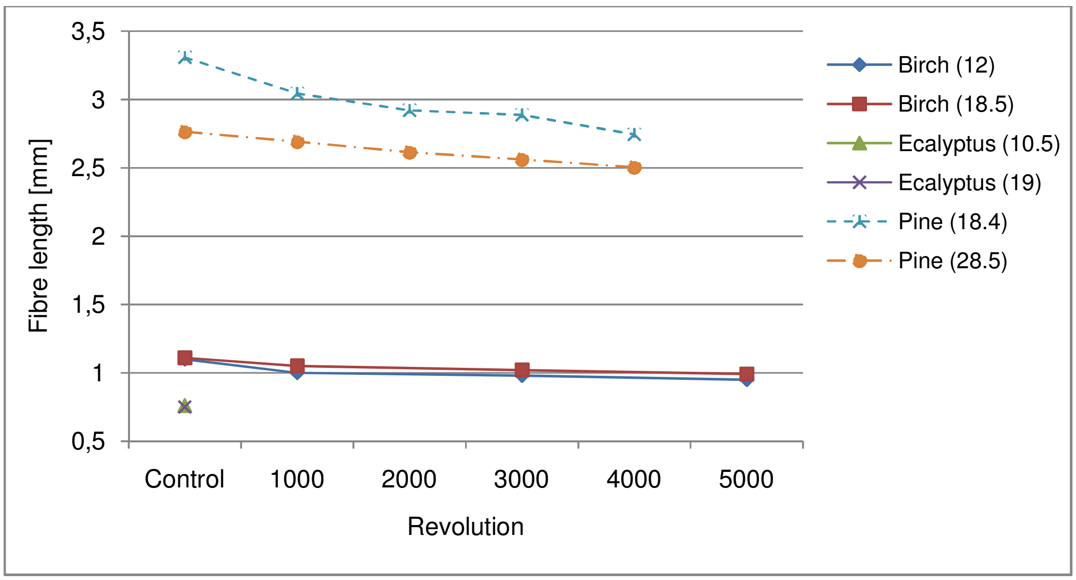

Chart 7.11 Fibre lengths versus number of revolutions in PFI mill

It is worth to notice that birch has 3 times shorter fibre length compared to pine fibres whereas eucalyptus has the shortest of all, which is nearly 4 times shorter compared to pine. Fibre length is one key factor among few important factors which decides the final product quality. These short fibres provide better optical properties but less strength compared to longer fibres of pine to the end product produced from them, which restricts their use in various products. In general, end product decides the usability of particular species for production. (Values for the above chart are available in appendix 2, table 2).

Comparison of tensile strength

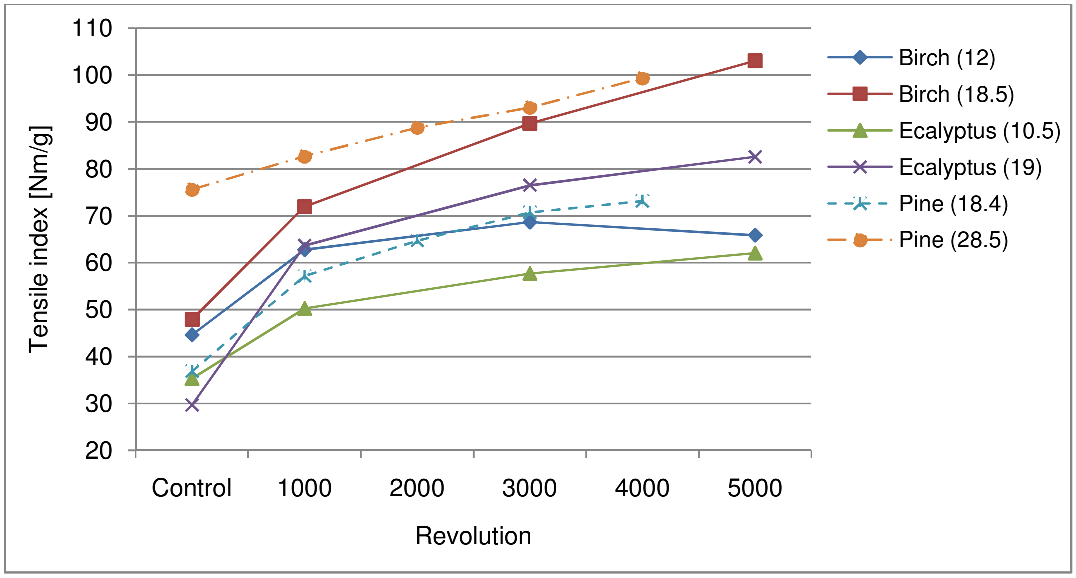

Chart 7.12 Tensile index versus number of revolution in PFI mill

Chart 7.12 implies that with the increasing amount of beating, the tensile strength was increasing in all species which is plotted as tensile index versus revolution in above chart. Beating affected tensile strength in positive direction as it increased the amount the fibrils on outer surface of fibre, increasing possibility of bonds between fibres which contributed directly by increasing the strength of paper web. Pine with high lignin content has the highest tensile strength before and after beating. On other hand highest increment could be noticed in eucalyptus pulp with high lignin content which has increment of 178%.

Here as pine was beaten up to 4000 revolutions only compared to other two which were beaten up to 5000 revolutions, it looks like birch and eucalyptus have higher tensile increment but if comparison is made at single point; say at 4000 revolutions pine had highest strength and the values can be seen in clear fashion. Again in terms of fibre length it was easy for pine to gain highest increment, as the possibility of bond formation is higher in case of long fibres of pine. (Values for the above chart are available in appendix 2, table 3).

Comparison of tear strength

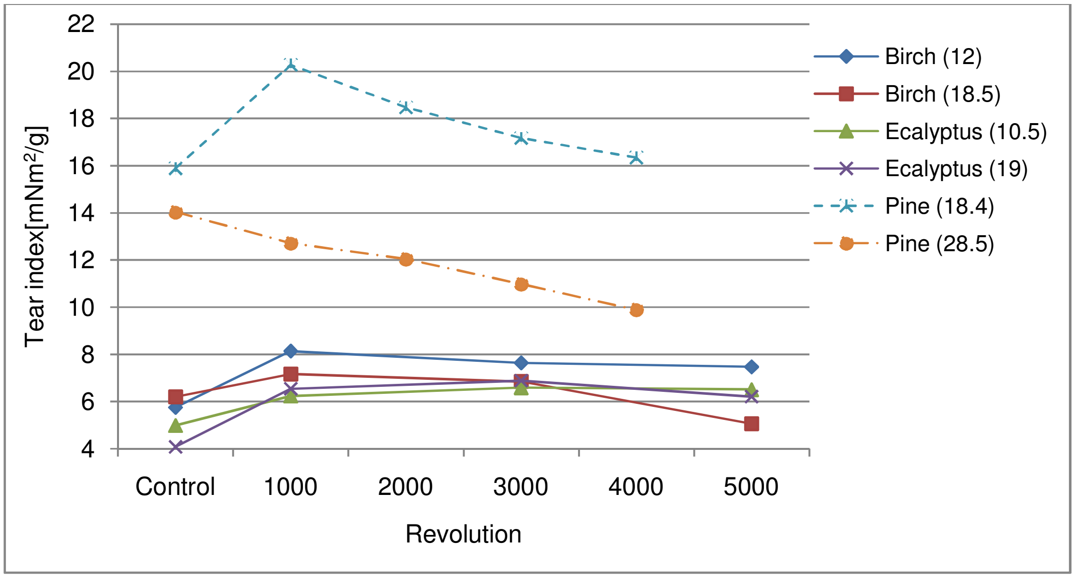

Chart 7.13 Tear index versus number of revolutions in PFI mill

From Chart 7.13 can be concluded that the tear strength of low lignin containing pulp of pine increased at first beating but later decreased, whereas for high lignin containing pulp, it decreased slightly after each beating. Compared with birch and eucalyptus pulps, tear strength of pine seems be far better. This was expected as the long fibres of pine has higher strength compared to birch and eucalyptus. (Values for the above chart are available in appendix 2, table 4).

Comparison of burst strength

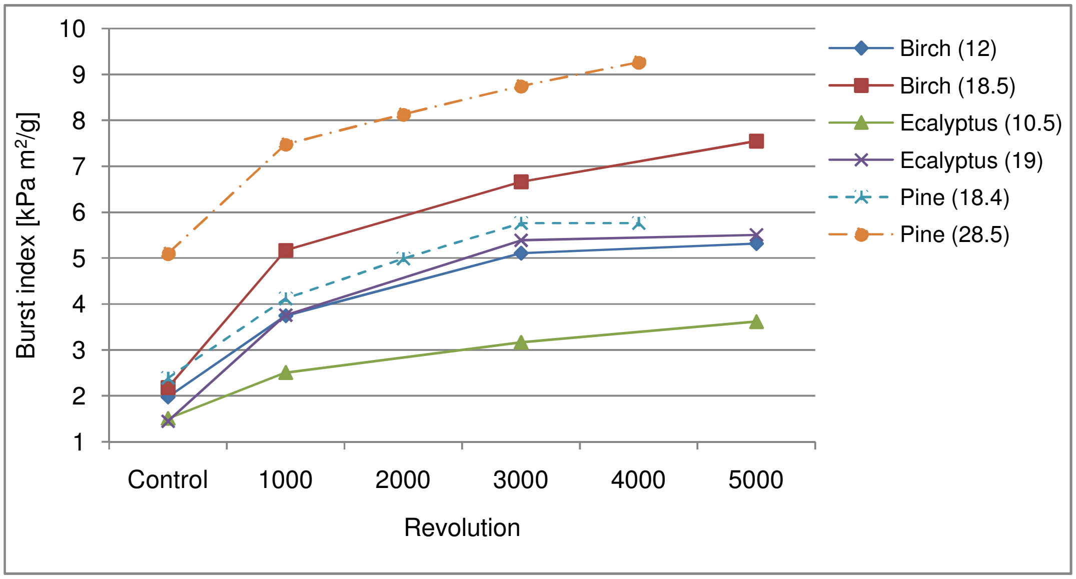

Chart 7.14 Burst index versus number of revolutions in PFI mill

In general, burst strength increased with increasing amount of beating. A notable change in bursting strength was seen in case of high kappa pulp of pine. In the above chart it seems that the low kappa pulp of pine has lower bursting strength compared with high kappa pulp of birch which is a little bit surprising. Others than that everything seems to correspond with the values from the literature. (Values for the above chart are available in appendix 2, table 5).

Comparison of bulk

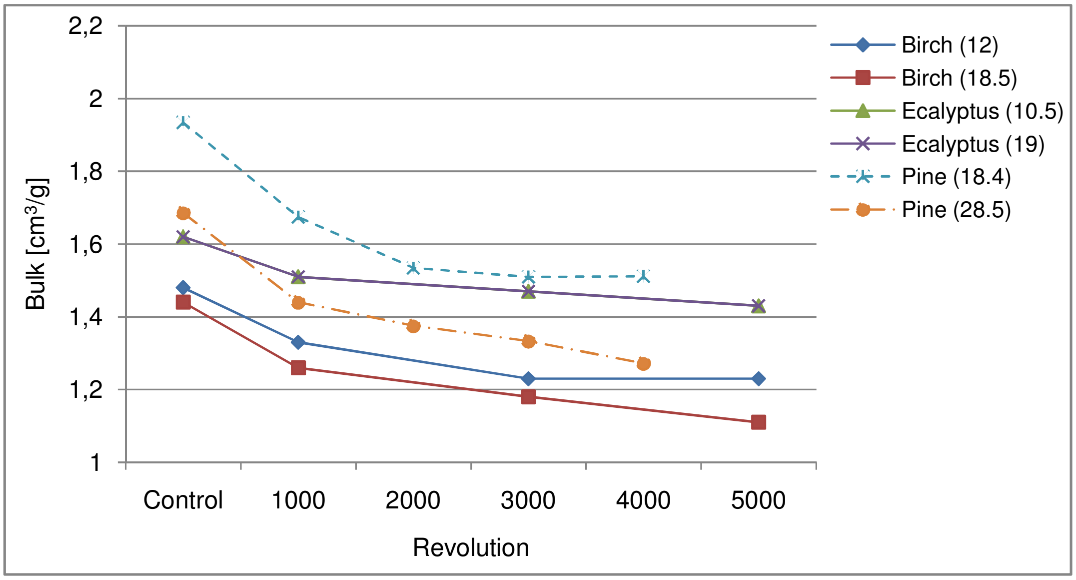

Chart 7.15 Bulk versus number of revolutions in PFI mill

As depicted in chart 7.15, the bulk of handsheets decreased sharply in case of pine compared to birch and eucalyptus after first beating. Although the general trend seems to be same, the response for beating seems to be faster for pine pulps. No significant difference was found between birch and eucalyptus but it seems that long fibres of pine tend to break which creates the secondary fines and increases the density of paper web, as result bulk decreases quite rapidly. (Values for the above chart are available in appendix 2, table 6).

Comparison of brightness

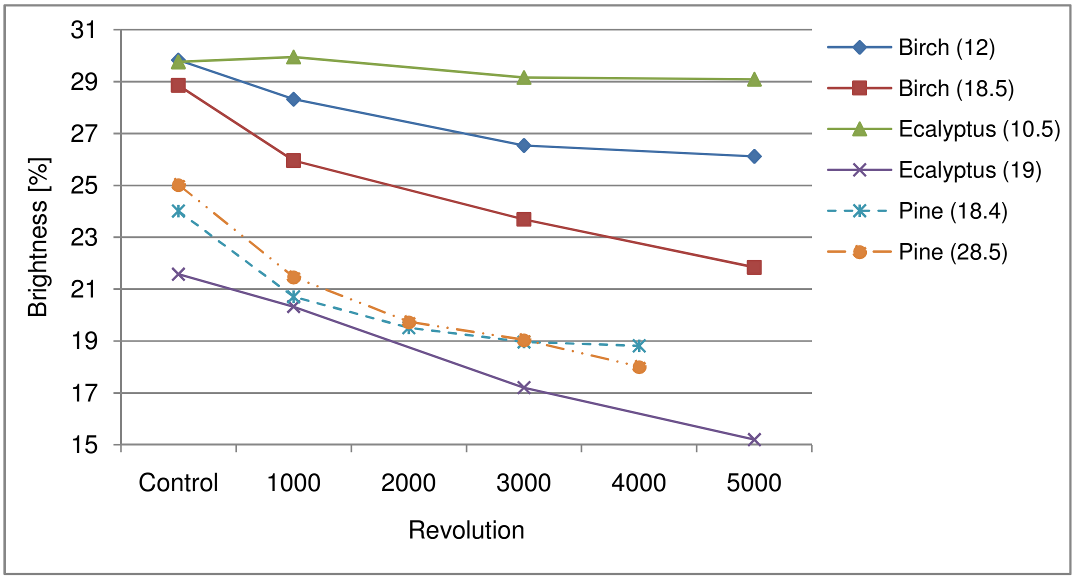

Chart 7.16 Brightness versus number of revolutions in PFI mill

Overall brightness decreased in all three species with the increased amount of beating but it could be noticed that brightness of birch was decreasing sharply compared to eucalyptus and pine. The high lignin containing pulp of eucalyptus had the highest decrement, by 30% which was followed by pine high lignin containing pulp whose decrement value was 28%. The brightness was highest in case of unbeaten birch followed by unbeaten eucalyptus which is at around the same level.

From the above chart it can be seen that the brightness values are higher for birch and eucalyptus compared to pine. Although the brightness was decreasing with increasing amount of beating in all pulps, the range was narrow for birch and eucalyptus, whereas for pine the range was very wide. That explains why birch and eucalyptus have higher brightness compared to pine. When beaten to same level, the brightness of pine dropped down sharply with higher decrement values compared to other two species. (Values for the above chart are available in appendix 2, table 7).

SUMMARY

The aim of this study was to investigate effects of beating on virgin Kraft fibre of pine. The two different pulps required for the experiment were cooked in laboratory scale in a batch digester with cooking liquor recirculation. As the result of cooking, pulp with kappa number 28.5 (so called high kappa) and pulp with kappa number 18.4 (so called low kappa) were obtained which were used for the entire experiments. The yield was 38.1% and 41.6% for low and high kappa pulps respectively. After washing, both pulps were beaten with the PFI mill refiner to 1000, 2000, 3000 and 4000 revolutions. Laboratory hand sheets were prepared from four different beaten pulp fractions and also from the unbeaten pulp fraction, from both cookings which were later used to measure optical and strength properties. Additionally, Sr number, residual alkali content, fibre length and water retention values were measured.

Some distinct differences in strength properties were observed in the thorough testing of laboratory handsheets. Beating brought significant changes in the fibre properties. Some of them were desired whereas others were undesired. Sr number was increased as the fibres drainability was increasing. Water retention values were rising after each beating. Beating increased the amount of fibrils on the surface of the fibres and flexibility, providing it with more surface area to bond and flexibly provides good web formation of fibre web; as a result tensile strength increased. As an important remark, beating had negative effect on the tearing strength. The bulk of sheet decreased with the increasing numbers of beating giving smooth compact paper. Whereas on the other hand, it was a real surprise to see that brightness was decreasing with the increased number of beating, and so did opacity. Fibre length decreased because of beating, which directly reduces the web strength of paper made from it. In addition to that the fibre length for high kappa cooking was a little bit small compared to low kappa cooking. Although being pine, exactly same material was not used in different cookings. This difference in fibre length likely affects the results in paper testing. Air permeability decreased to a quite low value after beating compared to unbeaten pulp sheet, which is a required property for paper making. Overall beat-

ing brought positive increments for all strength properties except tear, opacity and brightness.

For the most part, tested, both pulp and paper, properties were in agreement with previous studies found in the literature. However, some properties e.g. bulk and air permeability were different than expected, being in fact just the opposite than awaited to be observed according to the literature.

The results obtained from the experiments were compared with the earlier study done on birch (*Betula pendula*) and eucalyptus (*Eucalyptus Grandis*). The experimental data for birch and eucalyptus truly depends on the earlier thesis (secondary source), so any mistakes or uncertainty in values for birch and eucalyptus do not concern this thesis. In addition to that the handsheet preparation method used was different compared to earlier work; sheets were pressed and then dried in earlier ones whereas in case of pine the sheets were just dried without pressing. This may influence the values to some extent.

In the evaluation of pine Kraft versus birch or eucalyptus Kraft pulp as the raw material of laboratory made handsheets, pine Kraft pulp revealed some promising features, e.g. better tensile, tear and bursting strengths. However, the most important properties for strong paper were emphasized in the evaluation. Based on the evaluation, the quality of laboratory made handsheets were far better in case of pine Kraft pulp used as the raw material than of birch or eucalyptus pulp.

In fact, depending on the criteria for evaluation, pine Kraft pulp is better suitable for certain paper or board grades than birch or eucalyptus Kraft pulp. In addition, in certain products a mixture of these pulps can be used to achieve quality and processability.

FIGURES

CHARTS

TABLES

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Experimental values of Pine

Table 1 Sr number [Srº]

Revolutions	Kappa 28.5	Kappa 18.4
control	13	12.0
1000	15	13.0
2000	18	14.0
3000	22	15.5
4000	27	17.0

Table 2 Fibre length [mm]

Revolutions	Kappa 28.5	Kappa 18.4
control	2.76	3.31
1000	2.69	3.04
2000	2.61	2.92
3000	2.56	2.89
4000	2.50	2.74

Table 3 Water retention value [%]

Revolutions	Kappa 28.5	Kappa 18.4
control	123%	139%
1000	139%	164%
2000	150%	169%
3000	155%	170%
4000	159%	182%

Table 4 Tensile index [Nm/g]

Revolutions	Kappa 28.5	Kappa 18.4
control	75.66	36.88
1000	82.72	57.18
2000	88.82	64.74
3000	93.12	70.73
4000	99.37	73.18

Table 5 Tear index [mNm^2/g]

Revolutions	Kappa 28.5	Kappa 18.4
control	14.04	15.89
1000	12.72	20.28
2000	12.05	18.47
3000	10.98	17.17
4000	9.89	16.35

Table 6 Burst index [kPa m^2/g]

Revolutions	Kappa 28.5	Kappa 18.4
control	5.10	2.39
1000	7.48	4.12
2000	8.14	4.99
3000	8.75	5.76
4000	9.27	5.76

Table 7 Bulk [cm^3/g]

Revolutions	Kappa 28.5	Kappa 18.4
control	1.69	1.93
1000	1.44	1.67
2000	1.38	1.53
3000	1.33	1.51
4000	1.27	1.51

Table 8 Air permeability [ml/min]

Revolutions	Kappa 28.5	Kappa 18.4
control	1389	4400
1000	710	2327
2000	282	1280
3000	103	676
4000	52	435

Table 9 Brightness [%] 3 (3)

Revolutions	Kappa 28.5	Kappa 18.4
control	25.03	24.01
1000	21.47	20.71
2000	19.75	19.51
3000	19.05	18.96
4000	18.02	18.81

Table 1 Sr number [Srº] 1 (2)

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	15	15	23	21	12.75	13
1000	20	21	26	2	13.25	15
2000					13.25	18
3000	30	44	28	42	13.50	22
4000					15.00	27
5000	50	79	36	54		

Table 2 Fibre length [mm]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	1.10	1.11	0.76	0.75	3.31	2.76
1000	1.00	1.05			3.04	2.69
2000					2.92	2.61
3000	0.98	1.02			2.89	2.56
4000					2.74	2.50
5000	0.95	0.99				

Table 3 Tensile index [Nm/g]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	44.7	47.87	35.36	29.71	36.88	75.66
1000	62.8	71.90	50.29	63.71	57.18	82.72
2000					64.74	88.82
3000	68.7	89.65	57.74	76.54	70.73	93.12
4000					73.18	99.37
5000	65.9	103	62.07	82.60		

Table 4 Tear index [mNm²/g]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	5.75	6.20	4.99	4.08	15.89	14.04
1000	8.14	7.17	6.24	6.54	20.28	12.72
2000					18.47	12.05
3000	7.64	6.85	6.59	6.89	17.17	10.98
4000					16.35	09.89
5000	7.47	5.06	6.51	6.21		

Table 5 Burst index [kPa m²/g]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	1.98	2.18	1.51	1.45	2.39	5.10
1000	3.75	5.17	2.51	3.76	4.12	7.48
2000					4.99	8.14
3000	5.11	6.66	3.17	5.39	5.76	8.75
4000					5.76	9.27
5000	5.32	7.55	3.62	5.51		

Table 6 Bulk [cm³/g]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	1.48	1.44	1.62	1.62	1.94	1.69
1000	1.33	1.26	1.51	1.51	1.67	1.44
2000					1.54	1.38
3000	1.23	1.18	1.47	1.47	1.51	1.33
4000					1.51	1.27
5000	1.23	1.11	1.43	1.43		

Table 7 Brightness [%]

	Birch (12)	Birch (18.5)	Eucalyptus (10.5)	Eucalyptus (19)	Pine (18.4)	Pine (28.5)
control	29.8	28.86	29.76	21.58	24.01	25.03
1000	28.3	25.96	29.95	20.33	20.71	21.47
2000					19.51	19.75
3000	26.5	23.69	29.16	17.21	18.96	19.05
4000					18.81	18.02
5000	26.1	21.84	29.09	15.20		

Cooking results

	kappa value	Yield	Residual alkali content	Active alkali per gram oven-dry wood	time (min)
High kappa pulp	28.5	41.6%	7.5	26%	79
Low kappa pulp	18.4	38.1%	7.3	30%	110

List of standards used at work. APPENDIX 4

1 (1)

- Determination of Kappa number of pulp - ISO 302 - 1981(E)
- Laboratory beating of pulp - PFI mill method - ISO 5264/2 - 1979(E)
- Determination of drainability of pulp by Schopper-Riegler method - ISO 5267/1 - 1979(E)
- Determination of fibre length - TAPPI single fiber mode
- Preparation of laboratory sheets for physical testing -- Part 2: Rapid-Köthen method- ISO 5269-1:1998(E)
- Determination of tearing resistance (Elmendorf method) - ISO 1974:1990(E)
- Determination of tensile properties - ISO 1924 - 1:1992(E)
- Determination of bursting strength - ISO 2758:1983(E)
- Determination of thickness, density and specific volume - ISO 534:2005 (E)
- Measurement of diffuse blue reflectance factor (ISO brightness) - ISO 2470 - 1977(E)
- Determination of opacity (paper backing) -- Diffuse reflectance method - ISO 2471 - 1977(E)
- Determination of water retention value (WRV) – ISO 23714:2007(E)
- Determination of alkali resistance - ISO 699:1982(E)
- Determination of air permeance (medium range) -- Part 3: Bendtsen method - ISO 5636-3:1992